Alpha decay of ^{216}At and the level structure of ^{212}Bi

C. F. Liang and P. Paris
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3 Centre National de la Recherche Scientifique, Bâtiment 104, F-91405, Campus-Orsay, France

R. K. Sheline
Departments of Chemistry and Physics, Florida State University, Tallahassee, Florida 32306
(Received 12 November 1993)

The level structure of ^{212}Bi has been studied by observing the alpha decay of ^{216}At which is in secular equilibrium with ^{220}Fr and ^{224}Ac. Eight states are observed and tentatively assigned to the configuration $\pi h_{9/2}\nu(g_{9/2})^3$ and three to the configuration $\pi h_{9/2}\nu(g_{9/2})^2 i_{11/2}$. These two lowest configurations in ^{212}Bi are compared with the corresponding configurations in ^{210}Bi and the calculations of Warburton.

PACS number(s): 21.10.−k, 23.20.Lv, 23.60.+e, 27.80.+w

I. INTRODUCTION

The level structure of ^{210}Bi has been thoroughly studied both experimentally and theoretically [1–20] because with just one proton and one neutron beyond the double closed shells of ^{208}Pb it represents an ideal testing ground for the *p*-*n* interaction and a variety of nuclear models. However, with just two more added neutrons the nucleus of ^{212}Bi has received relatively little attention either experimentally or theoretically. Recently Warburton [21], using the Kuo-Herling shell model space [18] calculated the β^- decay rates for the ground state and the two isomeric states of ^{212}Bi in order to suggest spin-parity values for the two isomeric states. In the process it was necessary to calculate the low-lying energy spectrum of ^{212}Bi.

^{212}Bi has been studied experimentally using the β^- decay of ^{212}Pb [22] which has provided evidence for four low spin states. Alpha decay studies of ^{216}At [22] have allowed the observation of a number of states, including those observed in β^- decay such as the tentative 0^- state at 238 keV which should not be populated in the alpha decay of the 1^- ground state of ^{216}At. Some of the spins and parities of these states are unknown. The alpha decay of a 27 min isomeric state at $\sim$ 250 keV in ^{212}Bi has been observed [22] to alpha decay to the 4^- and 5^- states in ^{208}Tl and β^- decay to states in ^{212}Po. This state was speculatively assigned $J^\pi = 9^-$. Recently, however, Warburton [21] has shown that the experimental logft values can only be explained if the isomeric state in ^{212}Bi at $\sim$ 250 keV has $J^\pi = 8^-$.

In this alpha decay study of ^{216}At we have observed a number of states in ^{212}Bi which were previously unobserved, assigned spins and parities to most of these states and shown that some of the previously observed states in ^{212}Bi proposed as a result of alpha decay do not exist. The main purpose of this study is to locate the lowest-lying configurations in ^{212}Bi such as $\pi h_{9/2}\nu(g_{9/2})^3_{9/2}$ with a view toward comparing these configurations with the lowest-lying configurations in ^{210}Bi and with the theoretical calculations of Warburton [21].

II. EXPERIMENTAL METHODS AND RESULTS

Mass separated sources of ^{224}Ac (2.9 h) were produced by the Orsay Synchrocyclotron in conjunction with ISOCELE. The selective fluorination method described previously [23] was used to separate Ac from the elements Th, Pa, Ra, and Fr. In this experiment an $\sim$ 10 g target of Th-Ce alloy was heated to 1100° while being bombarded with $\sim$ 1 μA of 200 MeV protons. Bombarding times of 30–48 h were used on several separate occasions. The fluorinating medium was CF_4 which was continuously passed over the target during the bombardment. $^{224}AcF_2{}^+$ ions (mass 262) were mass separated with collected activity varying from 5×10^4 to 2×10^5 ions/s. The activity was collected for 2 h after which it was transported by tape into two different experimental setups.

In one experiment the tape moved the activity between alpha and gamma planar Ge detectors in 180° close geometry. The alpha detector had a full width at half maximum resolution of 17 keV, while the resolution of the gamma detector was $\sim$ 600 eV at 100 keV. Singles alpha and singles gamma spectra and alpha-gamma coincidence measurements were simultaneously recorded.

In the other experiment the ^{224}Ac activity was moved into the uniform field of a magnetic selector which deflected the electrons onto a cooled 6 mm thick Si(Li) detector. Two additional coax Ge gamma and alpha detectors were available for coincidence measurements. Singles alpha and electron spectra and alpha-electron, alpha-gamma, and electron-gamma coincidence measurements were recorded simultaneously.

It must be recognized that the 2.9 h ^{224}Ac activity after a few minutes has in secular equilibrium the 27.4 s ^{220}Fr, and the 0.30 ms ^{216}At. Thus the alpha spectrum of ^{224}Ac has in equilibrium with it the alpha spectrum of ^{220}Fr and ^{216}At. This alpha spectrum taken in coincidence with all gamma rays is shown in Fig. 1. Alpha grouping belonging to ^{224}Ac, ^{220}Fr, and ^{216}At are bracketed and energies in keV are indicated for the alphas of ^{216}At populating

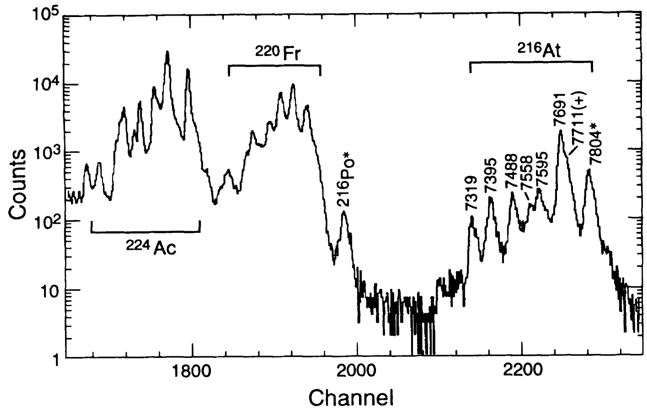

FIG. 1. Alpha spectra observed in coincidence with all gamma rays following alpha decay of ^{224}Ac, ^{220}Fr and ^{216}At. The energies of the alpha groups in ^{216}At are labeled in keV. The groups with (*) are random coincidences of ground-ground alpha decay. The 7711 keV (+) group is the sum peak from the 7691 keV alpha and the 24 keV electrons from the K shell of the 115 keV $M1$ gamma transition.

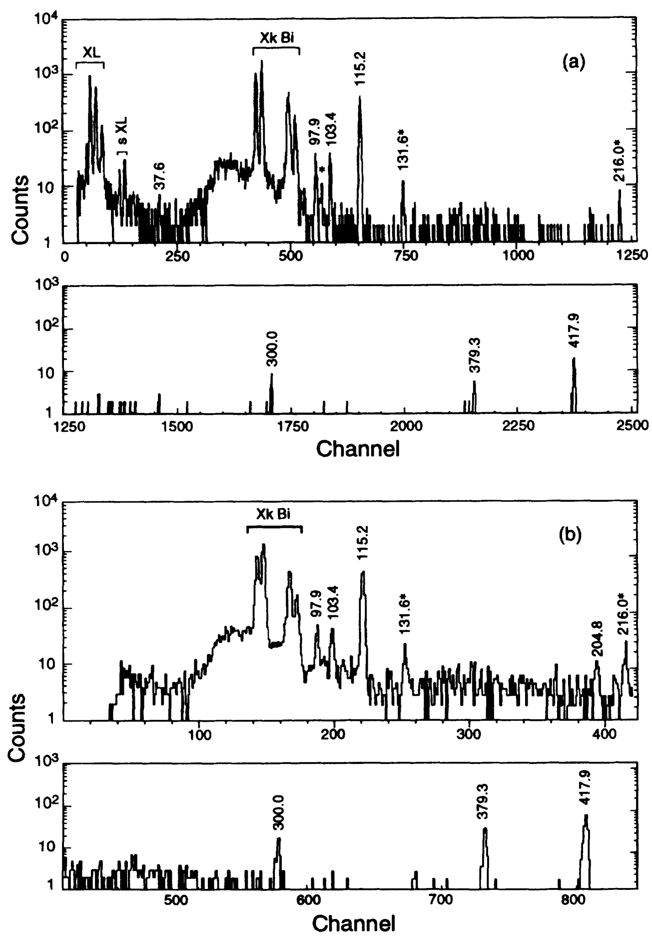

FIG. 2. (a) Gamma spectrum with planar Ge detector coincident with all alpha groups in ^{216}At (Fig. 1). (b) Gamma spectrum with coax Ge detector coincident with all alpha groups in ^{216}At (Fig. 1).

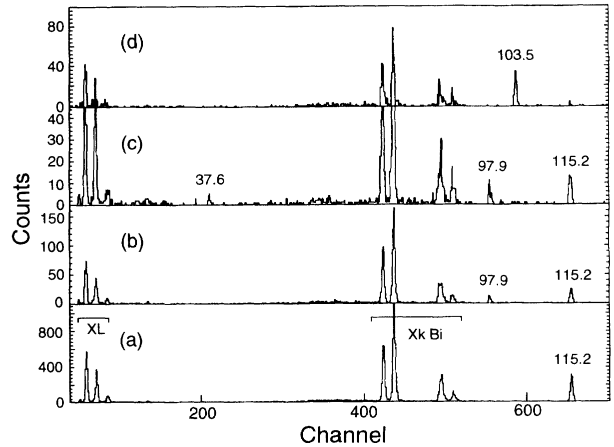

FIG. 3. Planar Ge spectra in coincidence with specific alpha groups in ^{216}At. (a) 7691 keV, (b) 7595 keV, (c) 7558 keV, (d) 7488 keV.

levels in ^{212}Bi. Figure 1 indicates quite clearly that there is very little overlapping between the alpha groupings which facilitates interpretation of the alpha-gamma and alpha-electron coincidence measurements.

Figures 2(a) and 2(b) present the gamma spectra obtained with planar and coax Ge detectors, respectively, coincident with all alphas in the ^{216}At alpha group of Fig. 1. Figure 3 presents the gamma spectra coincident with specific separated alpha groups. Gamma rays arising from transitions in ^{212}Bi are labeled by the energies in keV. X rays are specifically labeled as are gamma rays from the chance coincidences from the transitions in ^{224}Ra. These gammas are present in very high intensity as a result of the 90% electron capture of ^{224}Ac into ^{224}Ra.

A representative internal conversion electron spectrum is shown in Fig. 4. Energies in keV and multipolarities are indicated together with K, L, and M conversion lines.

Table I lists all of the gamma rays, their energies, intensities, and multipolarities when available, assigned to ^{212}Bi together with the assignment of the transitions in the level scheme.

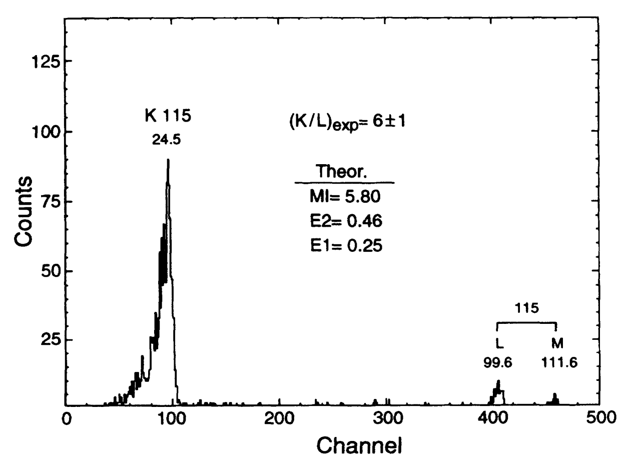

FIG. 4. Internal conversion electron spectrum in ^{212}Bi in coincidence with the 7691 keV alpha group.

TABLE I. Gamma-ray transitions in ^{212}Bi seen in coincidence with ^{216}At alpha particles.

E_γ (ΔE_γ) keV	$I_\gamma(\Delta I_\gamma)/10^3\alpha$	Levels Init.⟶Final	Multi-polarity	Multipolarity Exp.	Theo. $M1$	Theo. $E2$	Theo. $E1$
37.6 (0.4)	0.03 (0.01)	250.7 ⟶ 213.1	$M1$	α_L(TOT) = 21 ± 6	27	530	1.0
97.9 (0.2)	0.20 (0.05)	213.1 ⟶ 115.2	$M1(E2)$	I_{xk}/I_γ = 7.5 ± 1.5	9	0.5	0.36
103.4 (0.2)	0.23 (0.05)	(381) ⟶ (278)	$M1(E2)$	I_{xk}/I_γ = 5.5 ± 2.0	7.5	0.5	0.32
115.2 (0.1)	2.70 (0.20)	115.2 ⟶ 0	$M1$	I_{xk}/I_γ = 5.0 ± 0.6	5.5	0.45	0.24
204.8 (0.5)	0.10 (0.03)	417.9 ⟶ 213.1					
300.0 (0.3)	0.25 (0.05)	415.3 ⟶ 115.2	$M1$	$^{212}\text{Pb} \xrightarrow{\beta^-} {}^{212}\text{Bi}$ [22]			
379.3 (0.3)	0.33 (0.07)	494.6 ⟶ 115.2					
417.9 (0.2)	1.30 (0.20)	417.9 ⟶ 0					
X^L	9.2 (1.2)						
X^K	20.2 (2.0)						

III. THE LEVEL SCHEME OF ^{212}Bi

A partial level scheme for ^{212}Bi is shown in Fig. 5. To the left the β^- decay of ^{212}Pb is shown and to the right the alpha decay of ^{216}At as measured in these experiments. Beta decay energies, intensities, and logft values [22] are shown to the far left. To the far right the energies, intensities, and hindrance factors of the alpha decay are tabulated. It should be noted that the alpha decay differs significantly from that summarized in the recent Nuclear Data Sheets [22]. Certain levels reported to be populated by alpha decay in previous experiments are not populated in these experiments and some levels populated in these experiments were not previously observed. The gamma transitions not observed in alpha decay are shown to the left; those not observed in β^- decay to the right and those common to both modes of population are shown in the center.

It should be noted that a high spin isomeric state previously postulated to have $J^\pi = 9^-$ is observed at ~250 keV. While this state is populated by alpha decay, the details of its population are not certain. It has been suggested [22] that it is populated from a 9^- state 413 keV above the ground state of ^{216}At. Because of the uncertainty this 413 keV state in ^{216}At is shown dashed in Fig. 4. There is, however, no doubt about the existence of the ~250 keV state with a 27 min half-life in ^{212}Bi. It alpha decays to the 5^+ ground state and the 4^+ first excited state in ^{208}Tl with large hindrance factors, and β^- decays to states in ^{212}Po in the energy range from 1.13 to 1.46 MeV [22].

The careful β^- decay studies of ^{212}Pb leading to states in ^{212}Bi have already been shown [22] to determine the spin-parities of $1^{(-)}$, $2^{(-)}$, $0^{(-)}$, and $1^{(-)}$ for the ground state, 115.183, 238.362, and 415.272 keV states, respectively. The only uncertainty involves the parity suggested [22] to be minus because of the similarity with the known negative parities in the ^{210}Bi nucleus including the ground state 1^- arising from the configuration $\pi h_{9/2}\nu g_{9/2}$ and the $1^{(-)}$ ground state in the parent ^{216}At arising from similar ground state $\pi(h_{9/2})^3\nu(g_{9/2})^5$ configuration. However, the $\nu g_{9/2} \xrightarrow{\beta^-} \pi h_{9/2}$ and $\nu(g_{9/2})^2_{0^+} \xrightarrow{\beta^-}$

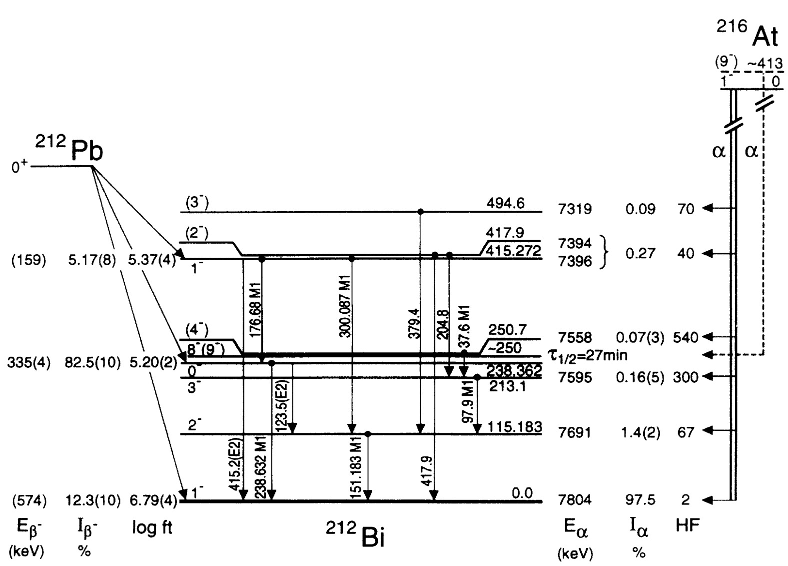

FIG. 5. Partial level structure of ^{212}Bi. The beta decay of ^{212}Pb together with the beta energies, intensities, and corresponding logft values [22] are shown to the left. The alpha decay of ^{216}At together with the alpha energies, intensities, and corresponding hindrance factors derived from this research are shown to the right. Gamma transitions together with their energies and multipolarities when known are shown as vertical arrows. Transition observed in both beta and alpha decay are shown in the middle; those observed only in beta decay, to the left; those observed only in alpha decay, to the right.

$(\pi h_{9/2}\nu_{9/2})_{0^-}$ decays in ^{209}Pb and ^{210}Pb both with logft values of 5.5 for these first forbidden decays is a strong indication that the $\nu(g_{9/2})^4_{0^+} \xrightarrow{\beta^-} [\pi h_{9/2}\nu(g_{9/2})^3]_{0^-}$ decay of ^{212}Pb with logft value 5.2 does populate the 0^- state in ^{212}Bi. Thus both the 0 spin and the negative parity of this state are affirmed. This also implies that the ground state, 115.183, 238.362, and 415.272 keV states, and the ground state of ^{216}At have negative parity. It should be noted that we did not observe 238.4 keV gamma rays with intensity limit $< 10^{-4}$ [Figs. 2(a) and 2(b)]. This implies that the alpha feeding to the 238.4 keV state is forbidden ($F_\alpha > 4000$).

In view of the hindrance factors of 300 and 540 populating the 213.1 and 250.7 keV states by alpha decay from the 1^- ^{216}At ground state, most probable $l = 2$ alpha decay and implied spins 3^- or 4^- can be suggested. The cascade of two consecutive $M1$ gamma transitions beginning at the 250.7 keV state fits with these assignments and suggests the sequence 3^- and $(4)^-$ for the 213.1 and 250.7 keV states since there is no observed transition from the 250.7 keV state to the 2^- state at 115 keV. States at 417.9 and 494.6 are observed on the basis of alpha decay from ^{216}At and coincident gamma decay. Tentative spin-parity assignments of (2^-) and (3^-), respectively, are suggested based on the gamma decay.

Recently, Warburton [21] has shown that the β^- decay to ^{212}Po cannot be explained using the 9^- postulated spin of the $\sim$250 keV ^{212}Bi state. In order to obtain the appropriate logft values a spin 8^- is required.

Finally it should be pointed out that there is a 7488 keV alpha transition (0.2%) in the alpha decay of ^{216}At in coincidence with a 103.4 keV $M1$ transition [Fig. 3(d)] which is difficult to explain. If one assumes that this alpha transition depopulates the 1^- ground state of ^{216}At, then a level in ^{212}Bi at 324$\pm$2 keV is defined which in turn populates a level at 221 keV via the 103.4 keV $M1$. However, the level at 221 keV has no observed decay and we see no evidence of isomerism. Furthermore, the 7488 keV alpha decay has a hindrance factor of 120 which implies an l transfer of $\sim$2. This in turn determines the spin state populated in ^{212}Bi by the alpha decay as 2^- or 3^-. Such a state would depopulate to the 1^-, 2^-, 3^-, and 4^- states known to exist below 324 keV in ^{212}Bi (see Fig. 5).

Perhaps the most reasonable solution to this dilemma is to assume that the known 57 keV state in ^{216}At [24] would be an isomeric state with tentative spin 4^- which has no other known mode of decay, and which alpha decays directly to the 381$\pm$2 keV (6^-) state in ^{212}Bi, which in turn populates a 7^- state at 278$\pm$2 keV following the 103.4 keV $M1$ transition. Presumably the 4^- state in ^{216}At also decays by a highly converted 22.4 keV $M1$ transition to the tentative 34.6 keV 3^- state in ^{216}At. A low energy 58$\pm$8 keV isomeric state in the neighboring nucleus ^{214}At has been suggested [25]. However, one must question why the tentative 4^- state in ^{216}At does not also have observable decay to the tentative 4^- state in ^{212}Bi at 250.7 keV. For that reason this suggestion must be considered very speculative. That is the reason it is shown in a separate tentative level diagram (Fig. 6).

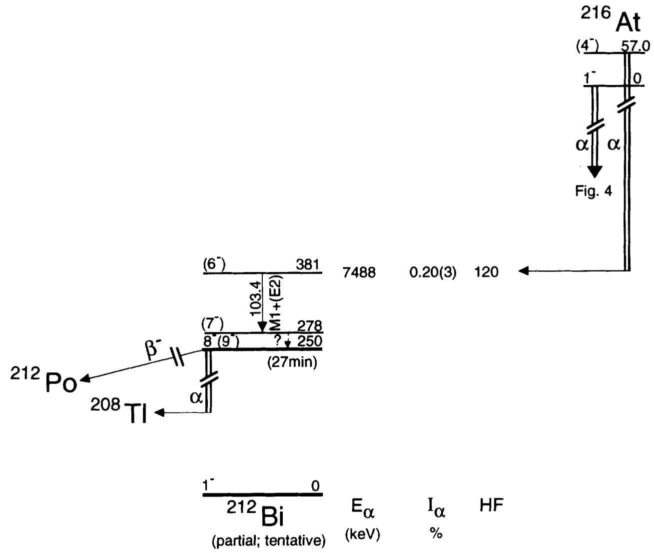

FIG. 6. More tentative part of the level structure of ^{212}Bi dealing with the high spin states. No decay from the (7^-) 278 keV state has been observed. The modes of decay of the 8^- (9^-) state at 250 keV to ^{212}Po and ^{208}Tl are indicated. For other details see the caption to Fig. 5.

The spins of the 381 and 278 keV states in ^{212}Bi are also uncertain and speculative. The hindrance factor of 120 for the alpha decay of the 57 keV (4^-) state of ^{216}At to the 381 keV suggests $l = 2$, implying 5^- or 6^- for the 381 keV state. Since the 381 keV state does not decay to the 250.7 keV tentative 4^- state, we prefer the 6^- assignment. The $M1$ assignment of the 103.4 keV gamma transition then suggests that the 278 keV state must have $J^\pi = 5^-, 6^-$, or 7^-. Since no $5^- \to 4^-$ transition is seen and only 5^- and 7^- states are expected, we prefer the 7^- assignment. This 278 keV 7^- state should then decay with a highly converted 28 keV $M1$ (or $E2$) to the 8^- (9^-) state at $\sim$250 keV in ^{212}Bi which in turn alpha and beta decays to levels in ^{208}Tl and ^{212}Po, respectively. All of this is shown in Fig. 6. Although it is speculative, it explains more of the features of the levels in ^{216}At and ^{212}Bi and their decays than other alternative schemes.

IV. DISCUSSION

Using the partial level scheme of Fig. 5 and the more tentative part of the ^{212}Bi level scheme of Fig. 6, it is possible to compare the level scheme of ^{210}Bi [12] and ^{212}Bi and compare each of them to the theoretical calculations of Warburton [21]. These comparisons are shown in Fig. 7.

Since we have complete confidence in the experimental levels of the $\pi h_{9/2}\nu g_{9/2}$ and $\pi h_{9/2}\nu i_{11/2}$ configurations of ^{210}Bi, the degree of agreement with the theoretical calculations of Warburton gives us a reading on how good we might expect the agreement between experiment and theory to be in the case of ^{212}Bi. Of course ^{212}Bi with four particles beyond the ^{208}Pb closed shell is a greater

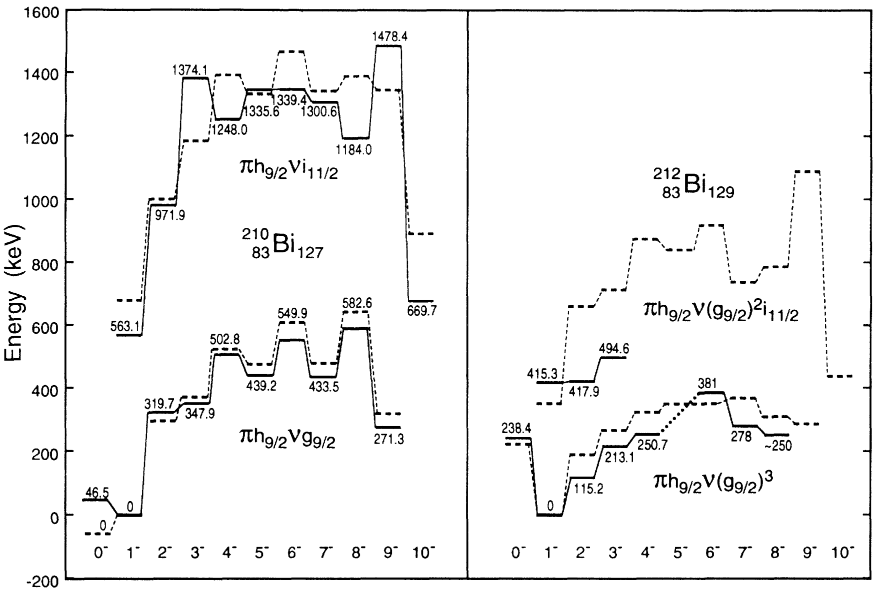

FIG. 7. Comparison of the level structures of ^{210}Bi (right) and ^{212}Bi (left) with the calculations of Warburton [21]. The solid levels are experiment and the experimental energies are given keV. The dashed levels are the calculations of Warburton. In the case of ^{212}Bi, the spins (0^- – 9^-) of the lowest energy are assigned to the $\pi h_{9/2}\nu(g_{9/2})^3$ configuration, while the second lowest (1^- – 9^-) and the lowest 10^- are assigned to the $\pi h_{9/2}\nu(g_{9/2})^2 i_{11/2}$ configuration.

theoretical challenge than ^{210}Bi with just two particles beyond the closed shell. However, the degree of agreement is somewhat similar and certainly encouraging.

In contrast with ^{210}Bi where the calculated energy relationship between the 0^- and 1^- states are not very well predicted, the agreement for ^{212}Bi is excellent (Fig. 7). In the case of ^{210}Bi the strong Nordheim [26] rule predicts that the 0^- state should be the ground state in agreement with the calculations of Warburton, but in contrast with experiment.

In general, just as in the case of ^{210}Bi for the $\pi h_{9/2}\nu g_{9/2}$ configuration, the calculations of Warburton predict the states of the $\pi h_{9/2}\nu(g_{9/2})^3$ configuration of ^{212}Bi somewhat higher than they are actually observed. Remembering the speculative nature of the 417.9 and 494.6 keV states, this trend is even more obvious in the case of the $\pi h_{9/2}\nu(g_{9/2})^2 i_{11/2}$ configuration of ^{212}Bi.

It must of course be remembered that the 4^-, 6^-, and 7^- states of the $\pi h_{9/2}\nu(g_{9/2})^3$ configuration are only tentative assignments, and the 2^- and 3^- states of the $\pi h_{9/2}\nu(g_{9/2})^2 i_{11/2}$ configuration of ^{212}Bi are also tentative. Furthermore the assumption has been made that the lowest energy state for each spin has been assigned to the $\pi h_{9/2}\nu(g_{9/2})^3$ configuration and the second lowest state of the appropriate spin, to the $\pi h_{9/2}\nu(g_{9/2})^2 i_{11/2}$ configuration (except 10^-) in the calculations of Warburton. Given the tentative nature of some of the spins and the assumption made in utilizing the calculations, the agreement is satisfactory.

Perhaps the best agreement between experiment and theory for ^{210}Bi occurs with the calculations of Kim and Rasmussen [27]. They correctly predict the order of the 0^- first excited state and the 1^- ground state and have generally good agreement with the other states of the Bi configurations. Their calculation utilizes the tensor force and involves a very sensitive fitting of the various force parameters. Unfortunately they have not attempted to calculate the 4-quasiparticle states of ^{212}Bi. They have, however, calculated the level structures of a number of other nuclei in this region, including ^{210}Po, ^{210}Pb, ^{208}Bi, and ^{208}Tl using the same force parameters with considerable success [28]. Perhaps their somewhat more phenomenological treatment mirrors more correctly the changing single particle energies as a function of proton and neutron number. It would seem to be of value to use this approach on some of the more challenging spectra like ^{212}Bi.

One of us (R.K.S.) wishes to thank the National Science Foundation for support under Contract No. PHY92-07336 with Florida State University and for the hospitality of the CSNSM and the IPN at the University of Paris-Sud, Campus Orsay.

[1] J.R. Erksine, W.W. Buechner, and H.A. Enge, Phys. Rev. **128**, 720 (1961).
[2] H.T. Motz, E.T. Jurney, E.R. Shera, and R.K. Sheline, Phys. Rev. Lett. **26**, 854 (1971).
[3] P.D. Ellegaard, P.D. Barnes, R. Eisenstein, and T.R. Canada, Phys. Lett. B **35**, 149 (1971).
[4] J.J. Kolata and W.W. Daehnick, Phys. Rev. C **5**, 568 (1972).
[5] C.K. Cline, W.P. Alford, H.E. Gove, and R. Tickle, Nucl. Phys. **A186**, 273 (1972).
[6] T.R. Canada, R.A. Eisenstein, C. Ellegaard, P.D. Barnes, and J. Miller, Nucl. Phys. **A205**, 145 (1973).

[7] D. Proetel, F. Riess, E. Grosse, R. Ley, M.R. Maier, and P. von Brentano, Phys. Rev. C **7**, 2137 (1973).
[8] D.J. Donahue, O. Hausser, R.L. Hershberger, R. Lutter, and F. Riess, Phys. Rev. C **12**, 1547 (1975).
[9] W.W. Daehnick, M.J. Spisak, R.M. Del Vecchio, and W. Oelert, Phys. Rev. C **15**, 594 (1977).
[10] W.W. Daehnick, M.J. Spisak, and J.R. Comfort, Phys. Rev. C **23**, 1906 (1981).
[11] R.L. Pointing, R.K. Sheline, E.T. Jurney, L. Nkwambiala, and B. Bompaka, Rev. Zair. Sci. Nucl. **7**, 1 (1986).
[12] R.K. Sheline, R.L. Pointing, A.K. Jain, B. bu Nianga, and L. Nkwambiaya, Czech. J. Phys. B **39**, 22 (1989).
[13] N. Newby and E.J. Konopinski, Phys. Rev. **115**, 434 (1959).
[14] I. Yu. Kharitonov, L.A. Sliv, and G.A. Sogomonova, Nucl. Phys. **28**, 210 (1961).
[15] Y.E. Kim and J.O. Rasmussen, Nucl. Phys. **47**, 184 (1963).
[16] T.A. Hughes, R. Snow, and W.T. Pinkston, Nucl. Phys. **82**, 129 (1966).
[17] J. Vary and J.N. Ginocchio, Nucl. Phys. **A166**, 479 (1971); J. Vary, dissertation, Yale University, 1970 (unpublished).
[18] G.H. Herling and T.T.S. Kuo, Nucl. Phys. **A181**, 113 (1971).
[19] C.W. Ma and W.W. True, Phys. Rev. C **8**, 2313 (1973).
[20] E.K. Warburton and B.A. Brown, Phys. Rev. C **43**, 602 (1991).
[21] E.K. Warburton, Phys. Rev. C **44**, 261 (1991).
[22] A. Artna-Cohen, Nucl. Data Sheets **66**, 171 (1992).
[23] R.K. Sheline, C.F. Liang, and P. Paris, Int. J. Mod. Phys. **5**, 2821 (1990).
[24] M.J. Martin, Nucl. Data Sheets **49**, 93 (1986).
[25] G.T. Ewan, E. Hagberg, B. Johnson, S. Mattsson, and P. Tidemand-Petersson, Nucl. Phys. **A380**, 423 (1982).
[26] L.W. Nordheim, Phys. Rev. **78**, 294 (1950); Rev. Mod. Phys. **23**, 322 (1951).
[27] Y.E. Kim and J.O. Rasmussen, Nucl. Phys. **47**, 184 (1965).
[28] Y.E. Kim and J.O. Rasmussen, Phys. Rev. **135**, B49 (1964).